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FOAM INFLATED RIGIDIZED TRUSS STRUCTURE DEVELOPED FOR AN SRS TECHNOLOGIES SOLAR CONCENTRATOR

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ABSTRACT

A foam inflated rigidized (FIR) truss structure to support a single chamber solar concentrator has been developed and demonstrated. This technology promises to advance the state of the art in construction of lightweight, deployable solar concentrators for solar thermal propulsion applications. In this paper the design, analysis, deployment and integration of this structure are discussed.

A FIR structure is a rigid composite tube that can be formed in space by inflating a resin impregnated fabric skin with a solvent swollen polymeric foam. Once inflated, the skin resin is cured using the available ultraviolet radiation. By using high strength and stiffness fiber materials, a stiff, strong, lightweight structure is produced (Lester, 1994).

INTRODUCTION

The dream of using the energy of the sun to propel a spacecraft is historical in nature. As early as 1956 a serious proposal for a solar powered spacecraft was voiced by Ehricke (1956). In the early 1960's Electro Optical Systems performed a successful feasibility demonstration at Edwards Air Force base (Wilner, 1963). However, due to funding constraints work on solar thermal propulsion was suspended until 1978 when Rocketdyne reopened the investigation. Under the direction of Gerald Naujokas of Edwards Air Force Base, Rocketdyne developed a functioning solar rocket engine (Shoji, 1985). Since that time development of solar thermal propulsion has continued at Phillips Laboratory Edwards. Kristi Laug is currently directing this effort. Phillips Laboratory has led the effort to develop and integrate the essential components of a solar thermal rocket.

A solar thermal rocket uses the sun's energy to heat cryogenically stored hydrogen to very high temperatures (3,000 K - 4,000 K). The heated hydrogen then exits a nozzle at high velocity converting thermal energy into kinetic energy resulting in a low thrust (<3lbs) high efficiency (600 - 1000 Isp) engine. A solar thermal rocket is composed of the following systems: 1) cryogenic storage and feed system, 2) absorber / engine, 3) solar concentrators, and 4) attitude control system. Development and integration of these components into a functioning solar rocket is a continuing goal of the Solar office at Phillips Laboratory.

SRS Technologies has been a leader in developing innovative solar rocket components. SRS's single chamber solar concentrator is such a design, (see Fig. 1), (Clayton, 1995). This concept consists of a large primary concentrator surface which is held in place by an inflated, transparent membrane. Support trusses connect the primary concentrator to the solar absorber engine. The proposed support structure for the single chamber concentrator is a foam inflated rigidized (FIR) beam truss structure. This paper will focus on the design, fabrication and integration of a FIR truss structure with an SRS Technologies single chamber solar concentrator.

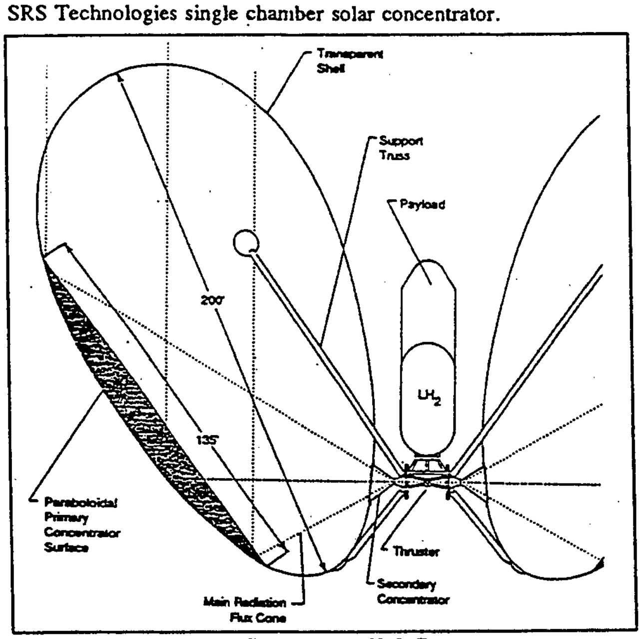

Figure 1. Solar Thermal Rocket with SRS Concentrators

FIR STRUCTURE

A FIR structure is a foam inflated fabric skin that is rigidized after inflation. Figure 2 shows a typical FIR beam in its predeployed state. The figure shows two foam filled canisters that are placed end-to-end. The canisters are filled with a solvent swollen polymer that will foam when exposed to vacuum. On the outside of the canisters is a woven fiberglass pre-deployed skin that has been impregnated with an ultraviolet curing resin. The woven pre-deployed skin is cut to the required length, fastened to the canisters, and then folded, accordion style, over the outside of each canister.

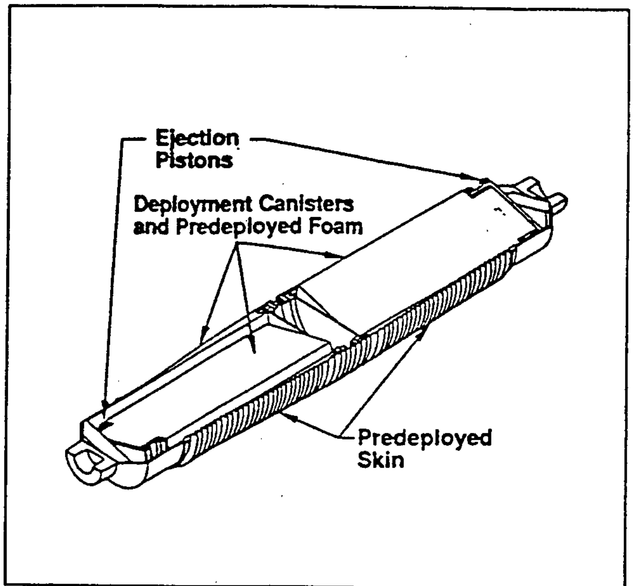

Figure 2. Pre-deployed FIR Beam

Inside each canister is an ejection piston. These pistons are actuated by pneumatic pressure or a pyrotechnic charge. Forward piston motion compresses the foam, eventually rupturing a thin foil membrane at the inner end of the canister. The pistons force the foam from the canisters into the woven pre-deployed skin. Solvent vaporization causes the foam to swell, and fill the pre-deployed skin. This results in the final beam shown by Fig. 3. Once deployed, solvent loss rigidizes the foam, and ultraviolet radiation cures the skin. Stiffness of the structure is derived from the E-glass composite skin. Foam eliminates the need for make up inflation gas of traditional inflatable systems, enhances buckling strength, and increases the structural damage tolerance (Lester, 1995a).

FIR CANISTER SELECTION

In Fig. 1 the conceptual design for the truss structure is shown as three tubular beam units cantilevered from the absorber attachment points to the single chamber concentrator. Initially a head-to-head canister design, described above, and a reservoir design were evaluated to form the truss elements. The reservoir design, (see Fig. 4), was selected because it significantly improves packaging efficiency over the canister design by putting the foam into a shorter, larger diameter reservoir. A larger foam reservoir allows the beam to be deployed from a single container. Instead of having two canisters placed head-to-head, one is replaced with a lightweight end fitting. This eliminates the canister weight at the end of the beam. This is very beneficial especially in cantilever situations such as the single chamber concentrator support structure.

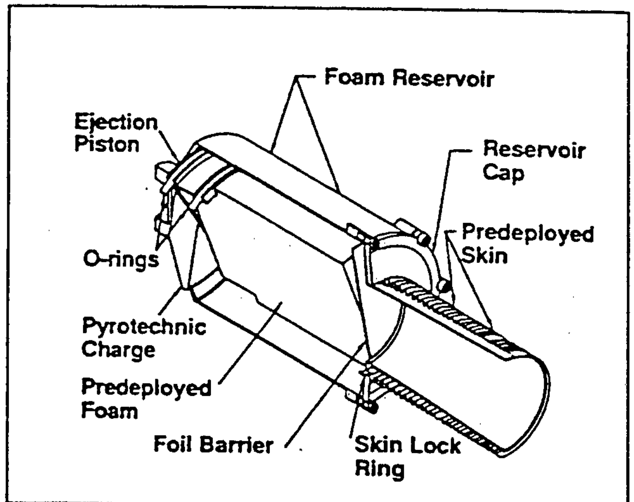

Figure 4. Reservoir Design

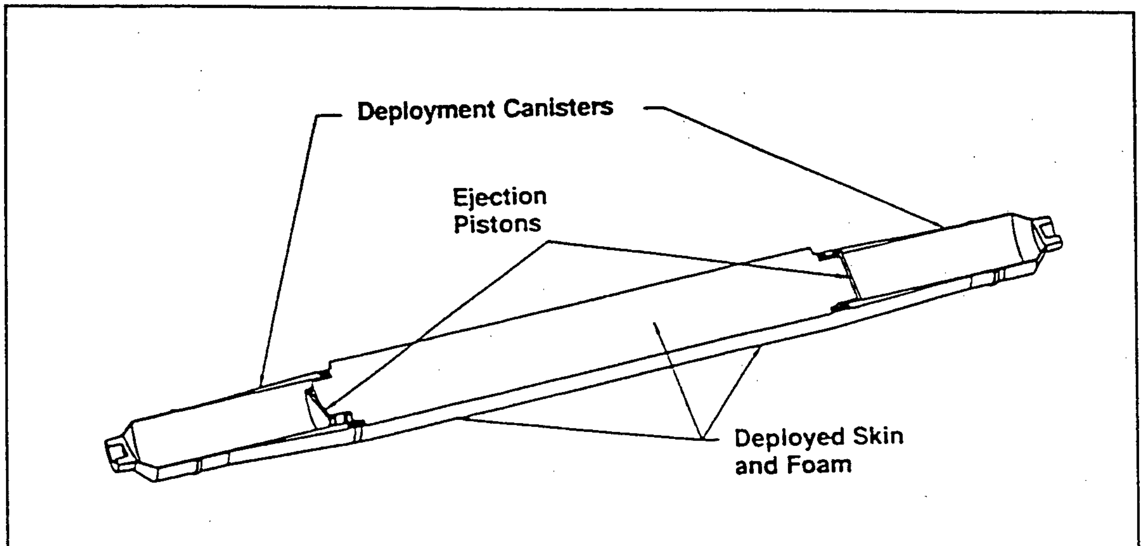

Figure 3. Post-deployed FIR Beam

DESIGN

The design effort evaluated several options to determine the one with the lightest weight, while minimizing deflections and beam stresses. Finite element techniques were used to predict the structural response of several proposed design geometries. Designs were also evaluated based on packaging efficiency, simplicity, and depolyability.

The design analysis defined the inflatable concentrator as a single point mass. This mass was located at the centroid of the inflated concentrator. Rigid rod elements extended from the point mass to locations near the inflatable concentrator surface where proposed beam attachment points were located. Beam elements, fixed at the end next to the attachment ring extended up to the inflatable concentrator surface near the rigid rod termination points. The beam ends were connected to the rigid rod elements using Coupled Degrees of Freedom (CDOF). CDOF's were used because they could be limited to transferring translational displacements only. This would prevent moment transfer between the beams and the rigid elements. This is valid because the inflatable concentrator cannot carry large transverse bending moments. CDOF's also can output force resultants. Therefore, forces obtained from the trade study could be input into SRS's inflatable concentrator finite element model to predict it's response.

Several designs were evaluated. The study looked at four different attachment points on the inflatable concentrator. One attachment point was at the very bottom, and three different attachment points up the side of the inflatable concentrator. Figure 5 shows the model geometry.

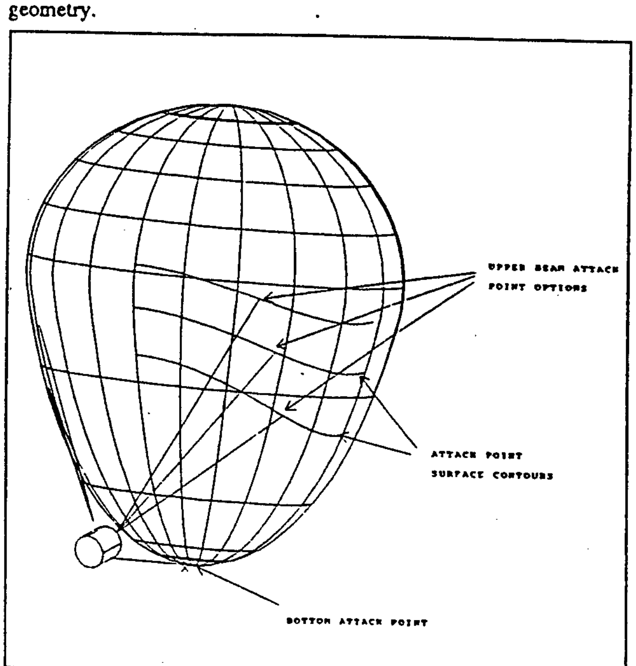

Figure 5. Beam Attachment Model Geometry

and arrangements were evaluated. Beam members ranged from 2" to 4" in diameter, and were combined in 1 to 4 element groups in parallel, trigonal, or rectangular arrangements. Figure 6 shows an example of the trigonal arrangement.

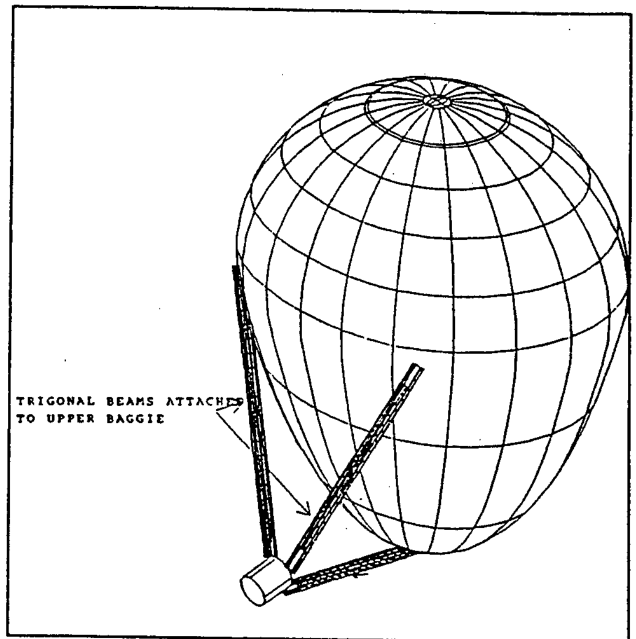

Figure 6. Trigonal Beam Design Option

The load was applied to the model through an acceleration vector parallel to the optical axis of the rocket. The acceleration of 0.003 g's is shown graphically in Fig. 7. This acceleration acted on the inflatable concentrator point mass and on the beam elements themselves.

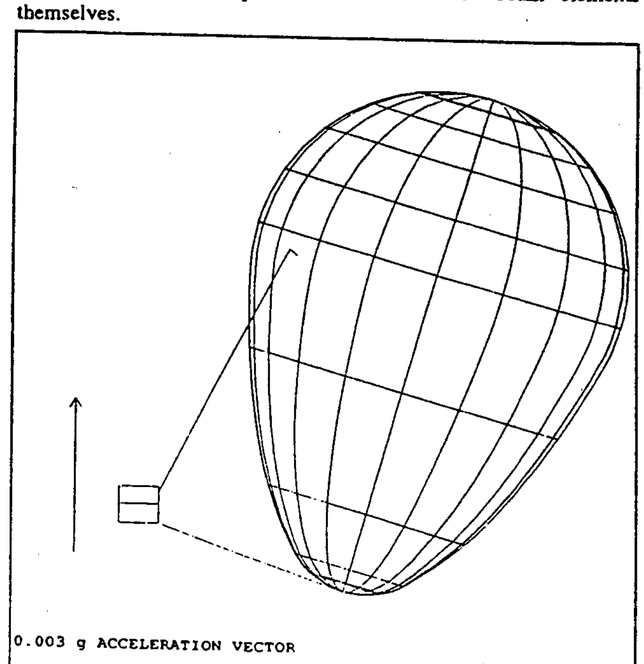

Figure 7. Acceleration Vector at 0.003 g

The analysis compared the responses of several support configurations to the acceleration load. Of primary interest were the beam weights, the maximum stresses in the beams, and the deflections of the beams and the inflatable concentrator.

The results are shown graphically in Fig. 8. This plot compares the inflatable concentrator centroid displacements to the estimated beam weights. In the plot the displacements decrease between the beam weights of 0.02 to 0.06 lbs. Between 0.06 and 0.07 lbs, the values appear to level off, with no significant improvement in displacement as the weight increases beyond 0.07 lbs. These results indicate that the optimal design is in the 0.06 to 0.07 lb range. The beam weights are those predicted by the model in the 0.003 g environment.

The beam stresses are the maximum compressive values. In all cases, the maximum stresses occur near the attachment ring because the beams are cantilevered from this location. The maximum stress in any case is 36.03 psi. This is an extremely low stress compared to the skin compressive capability which has been measured to be approximately 6000 psi (Cannon, 1995).

The final design derived from this analysis selected a 2.75 inch diameter beam. The design includes two beams attached to the upper attachment points and two to the bottom of the inflatable concentrator. The bottom beams were attached side by side instead of one on top of the other as with the two tube beam concept. This provided lateral stability.

The 2.75 inch diameter beam was chosen as a compromise between pre-deployed foam volume, weight, and modeled concentrator deflection values. From the model the inflatable concentrator deflection was predicted to be 0.025". A second reason for selecting the 2.75 inch diameter beam, was that this diameter corresponded closely to historical deployments that used a 2.6 inch diameter beam(Cannon 1995). Figure 9 shows the pre and post deployed configuration of the FIR truss structure final design. Figure 10 shows the truss structure integrated with SRS Technologies single chamber concentrator.

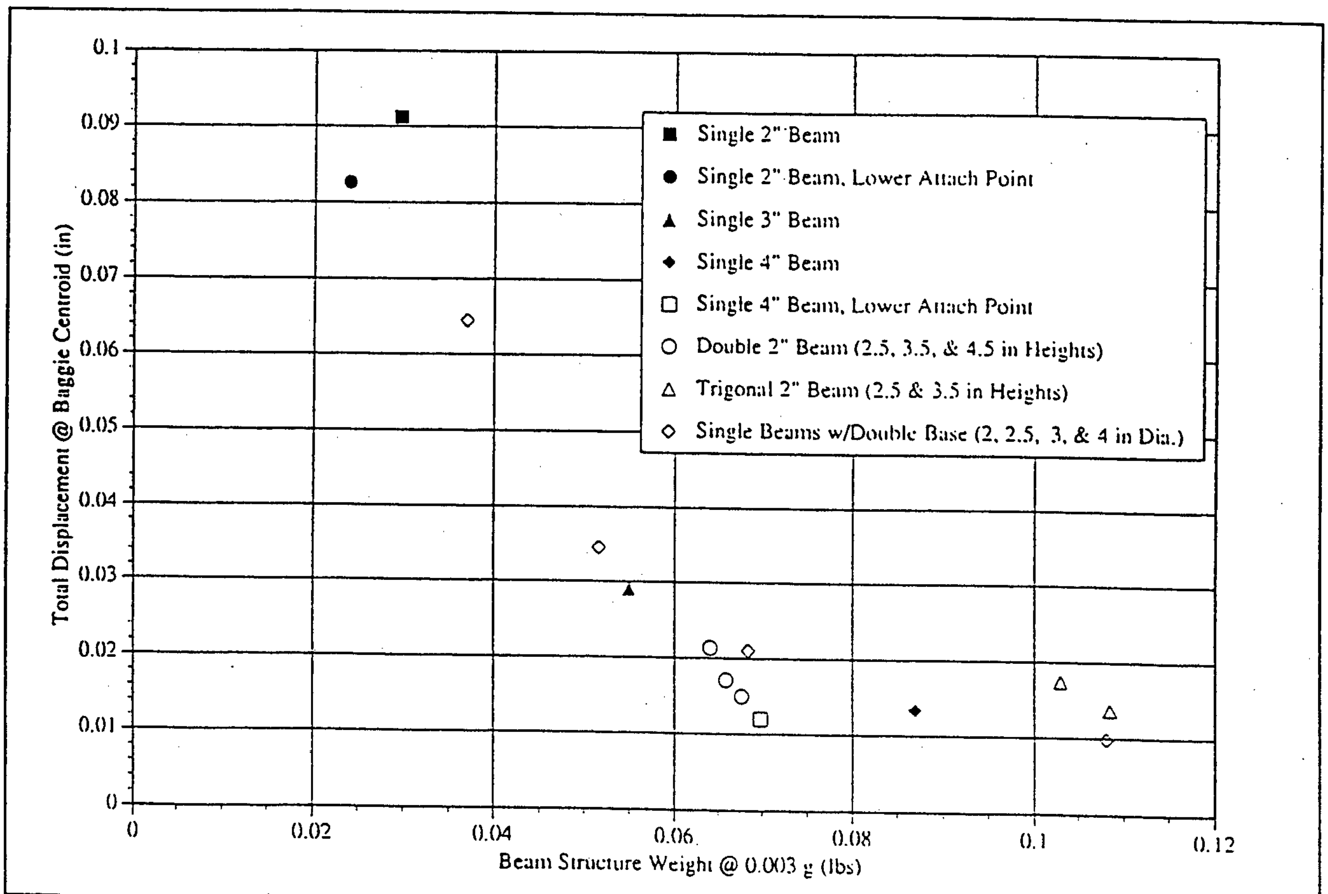

Figure 8. Plot of Estimated Beam Weight at 0.003 g vs Concentrator Centroid Deflection

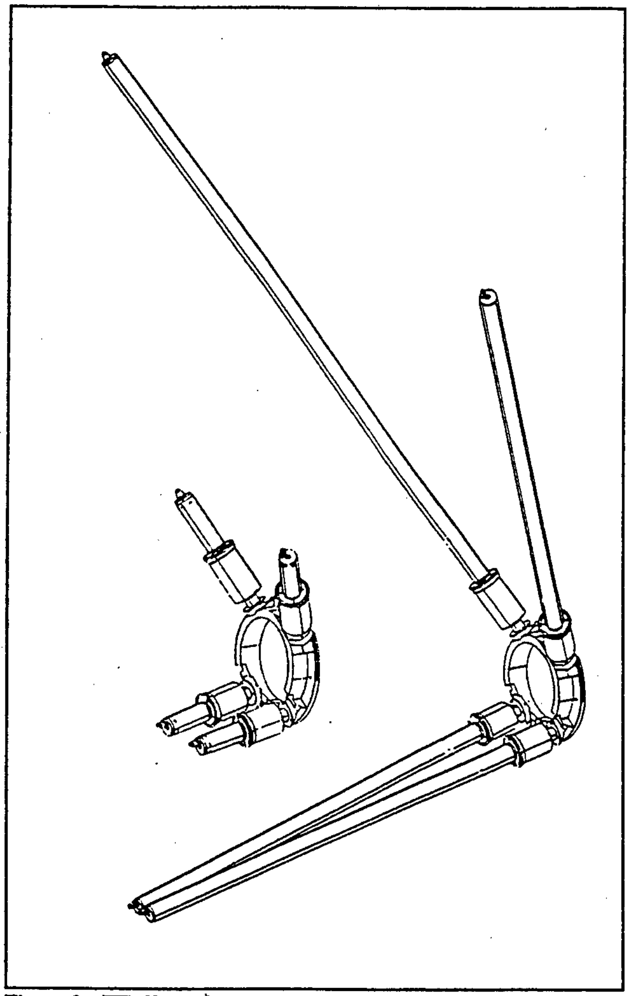

Figure 9. FIR Truss Structure

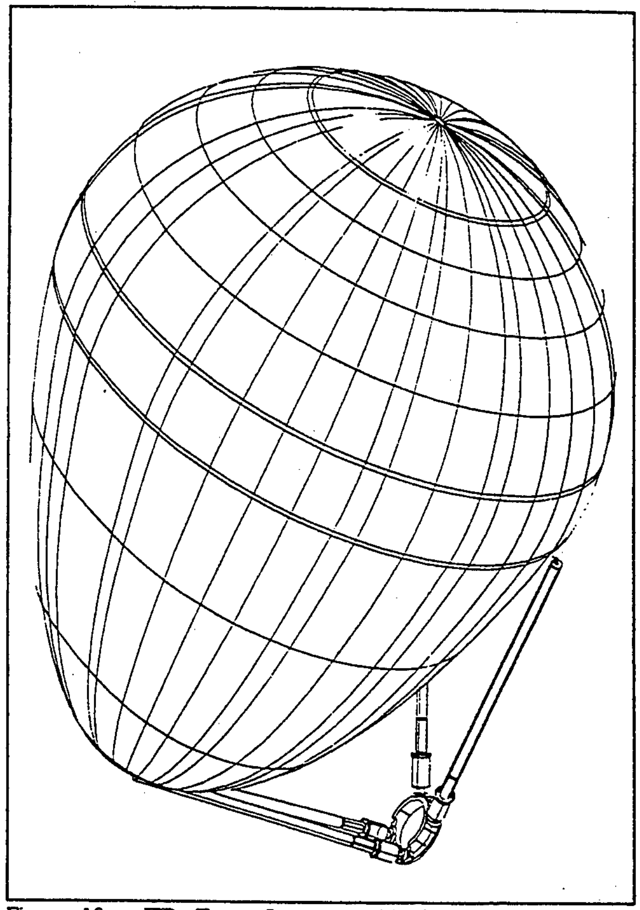

Figure 10. FIR Truss Structure with SRS Single Chamber Concentrator

COMPONENT DESIGN

The truss design shown in Fig. 9 is composed of several components. These consist of two long beam assemblies (115 inch), two short beam assemblies (78 inch) and the base attachment ring.

The design of the base attachment ring incorporates the inflatable concentrator surface with the reflector and rocket engine geometry. The base ring diameter is set at 20". The angles of the mounting surfaces on the base ring are designed to position the ends of the deployed truss structure tangent to the inflated single chamber concentrator. These mounting surfaces can be seen in the sketch of the ring shown by Fig. 11.

The beam assemblies are composed of the reservoir, fabric skin and fabric skin end cap. The length of the reservoirs are based on the solution to a set of simultaneous equations which took into account final beam length, foam expansion ratio, and reservoir internal volume. The foam is assumed to have a 5 to 1 expansion ratio based on optimum values determined in the Gossamer Structures program (Lester, 1995a). Figure 12 shows an exploded sketch of the reservoir assembly.

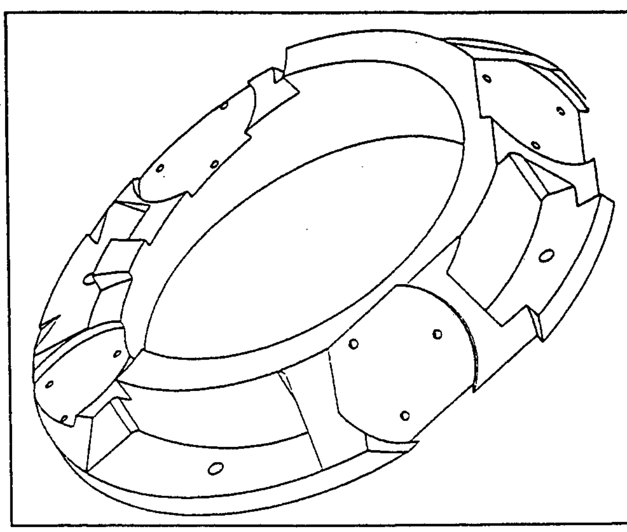

Figure 11. Base Attachment Ring

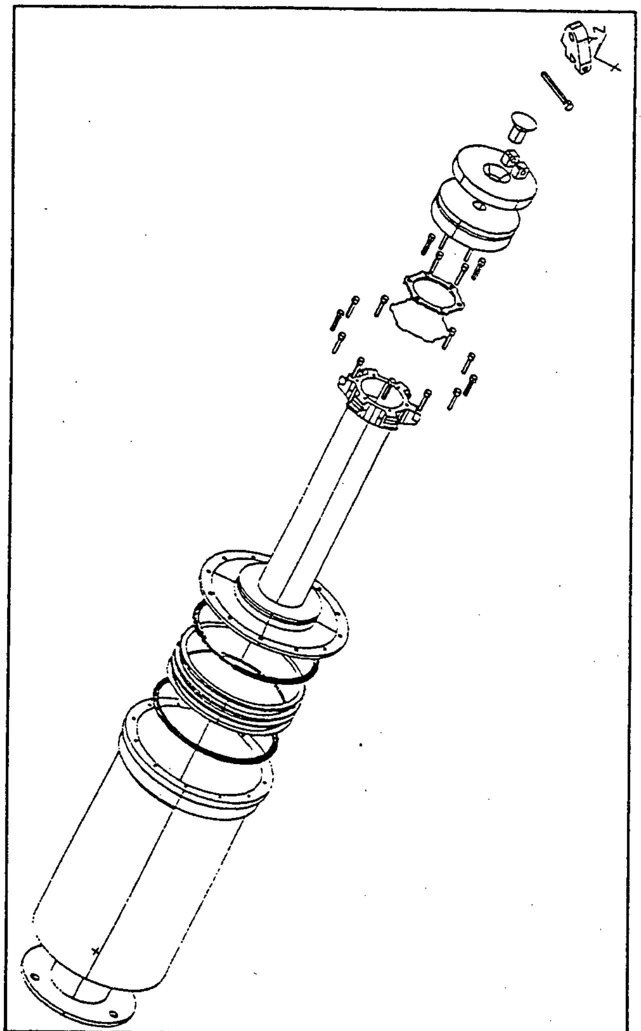

Figure 12. Exploded Sketch of Reservoir Assembly

The joint between the fiberglass skin and the deployment hardware was improved over previous designs. Past designs used a sliding joint that proved to be unpredictable. The new joint design used a fixed attachment point. This reduced length variations observed during deployment from 4% for the slip joint design to 0.5% for the fixed point design.(Cannon, 1995).

Several design constraints were placed on the method of attaching the beams to the base ring. Since this was the first attempt at deploying beams of such great length, there were concerns over length variation and straightness. Therefore, the beam attachment method needed to have both length and angular variational capability. The solution to this problem was to include a flange on the end of the reservoir. The flange has three holes which matched holes on the mounting ring. Attaching the reservoir to the base ring was accomplished using nut and bolt assemblies with spherical washers. This design allowed for $\pm$ 0.5 inch axial travel and 8° to 10° rotation. Figure 13 shows a diagrammatic representation of the reservoir attachment method.

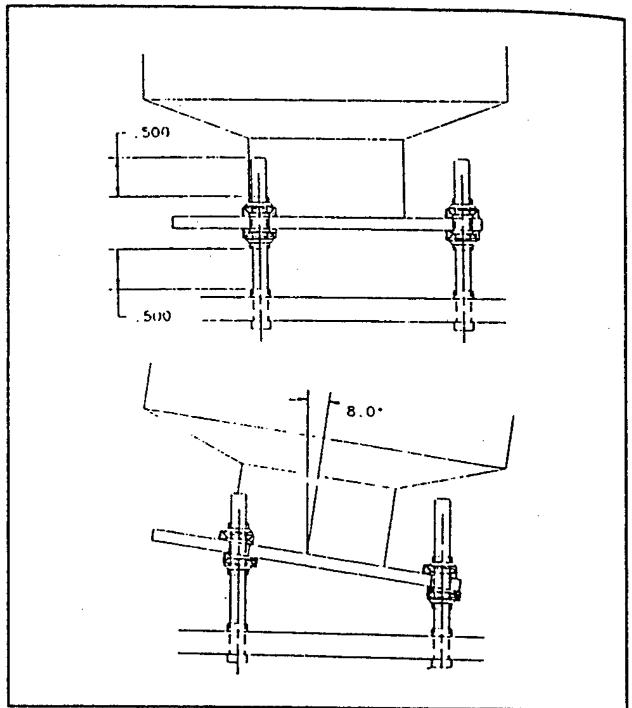

Figure 13. Sketch of Reservoir Attachment Method

DEPLOYMENT DEMONSTRATION

The deployments were conducted in the Phillips Laboratory's Space Environmental Test Facility (SPEF) chamber. The beams were deployed vertically down since no suitable method for deploying with the attachment ring could be determined. Deploying the beams in any direction other than vertical would have resulted in warpage of the beams due to gravity. The reservoirs were attached to a support structure which was suspended from the lid of the SPEF chamber.

To prepare for deployment the SPEF chamber was evacuated to a pressure of < 100 millitorr. A single beam (one of the longer beams) was deployed first to demonstrate feasibility.
The remaining three beams were then deployed as a group. The four beams were then mounted on the base attachment ring. Figure 14 shows a photograph of the deployed FIR truss strcuture.

A summary of the achieved lengths of the deployed beams is included in Table 1. The length variation between the beams has been attributed to two factors. First, when cutting the pre-deployed skins, hand tension was used to prestress the material. This method resulted in variation in the pre-deployed skin length. Second, the pre-deployed skin material, when received from Fabric Development Incorporated, was 2.90 inches in diameter, whereas, the design specified 2.75 inches in diameter. When the pre-deployed skin was attached to the 2.75 inch diameter end pieces, slight wrinkling of the pre-deployed skin occurred. This caused a slight variation in length around the circumference of the beam.

Both of these problems can be easily solved to eliminate the majority of beam length variation. Inflating the pre-deployed skin with air to uniformly pretension it prior to cutting will solve the first problem. Carefully sizing the fabric pre-deployed skin and end fittings will eliminate the second.

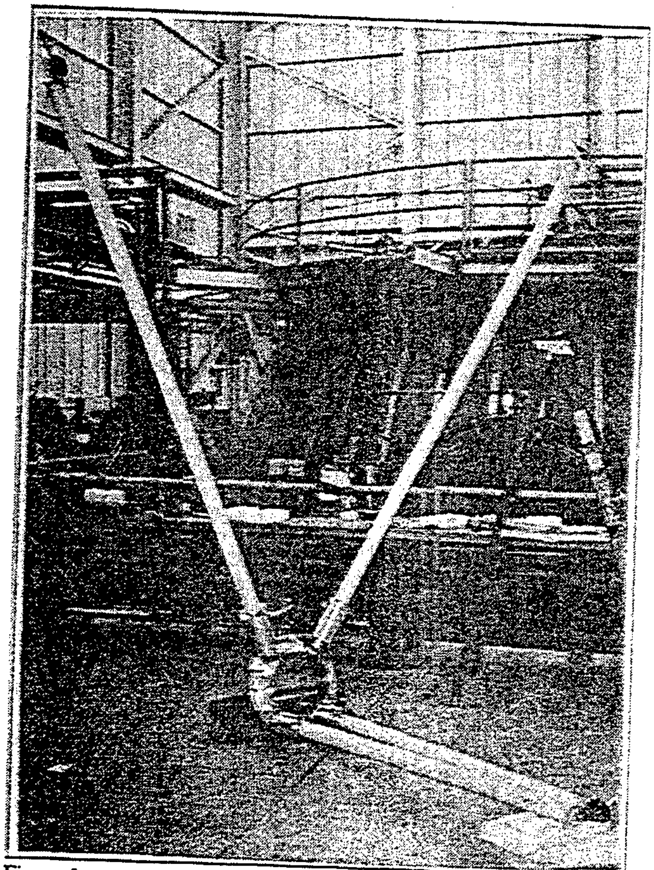

Figure 14. Assembled FIR Truss Structure

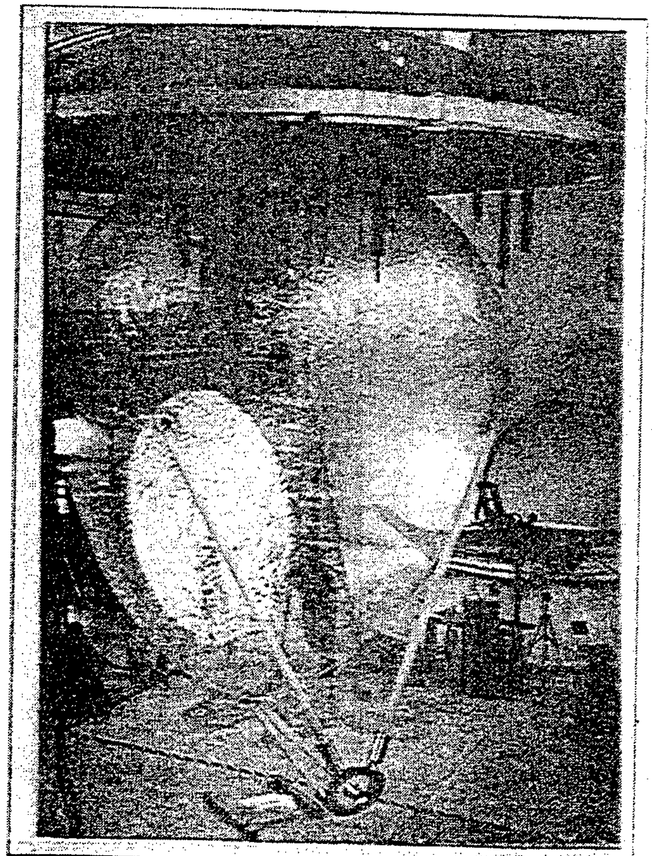

Figure 15. SRS Single Chamber Concentrator with FIR Truss Structure

Table 1. Deployed Hardware Statistics

Description	Measured Length (in.)	Predicted Length (in.)	Δ	%Δ (in.)	Mean (in.)	.3σ (in.)	3σv %
Long Beam 1	115.75	115.16	0.58	0.51	115.5	0.93	0.8
Long Beam 2	115.31	115.16	0.15	0.13			
Short Beam 1	78.81	78.34	0.37	0.47	78.78	0.13	0.16
Short Beam 2	78.78	78.34	0.41	0.52			

INTEGRATION

The final step in our study was the integration of the support structure with the inflated concentrator. The beams that were deployed separately, were mounted on the base attachment ring to form the assembled truss structure shown in Fig. 14. This was accomplished by suspending the beams and the base attachment ring from the SPEF chamber lid. The inflated concentrator was then moved under the lid and mated with the suspended truss structure. The inflated concentrator and support truss structure coupling operation was easily accomplished. The ease of this integration confirmed the validity of the solid design model and achieved accuracy of the deployed beams. Figure 15 shows the integration of the support structure and the inflated concentrator.

CONCLUSIONS

A FIR truss structure for a single chamber concentrator of a solar thermal rocket was designed, analyzed, fabricated, and deployed. This support structure was integrated with an SRS Technologies single chamber concentrator. The approach included a study to determine the optimum support structure design. This study used finite element techniques to determined the number and diameter of the beams, and their attachment points on the inflatable concentrator. Each test case predicted the support structures weight and deflection at an acceleration of 0.003 g. The study predicted an optimum configuration using four, 2.75 inch diameter beams. Two beams were attached to a single point at the base of the inflated concentrator, and two more extended to upper attachment points on the side.

A foam reservoir canister design was used to improve packaging efficiency. The reservoir design decreases beam predeployed length by packaging the pre-deployed foam in a shorter, larger diameter cylinder. Predeployed beam length decreases by 30% when compared to the canister design. The one drawback to the reservoir design is that weight increases approximately 15%. Another significant improvement incorporated in the reservoir design over previous designs was an improved joint between the fiberglass skin and the deployment hardware. This development significantly improved deployment reproducibility.

The culmination of the program was the deployment of the beams at Philip's Laboratory SPEF Chamber. Four beams were successfully deployed. Two at 115 inches in length and two at 78 inches in length. These beams were integrated with the support ring and then attached to the inflated concentrator. This final integration completed the accomplishment of all program goals.

Continuing research of FIR truss technology will focus on reducing weight. Significant improvements, (~ 60%), can be achieved by optimizing the deployment hardware and minimizing the density of the inflation foam (Lester, 1995b).

ACKNOWLEDGEMENTS

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